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OAO IMAGE CONVERTER RESEARCH

(NASA Grant NsG-276-62)

Final Report

1963

Prepared for

National Aeronautics and Space Administration
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FOREWORD

This report summarizes the results of a study carried out under NASA Research Grant NsG-276-62 to define the performance requirements that will have to be met by image converters to be used in conjunction with advanced generations of orbiting astronomical telescopes which NASA hopes to launch within the next decade.

The author gratefully acknowledges the help generously extended in the form of discussions and correspondence with many astronomers and vacuum tube engineers engaged in some phase or other of current research on imaging devices.

Responsibility for the conclusions and recommendations contained in this report rests solely with the author, however.

Respectfully submitted,

LABORATORIES FOR APPLIED SCIENCES

Jay Burns

Jay Burns
Principal Investigator

1. INTRODUCTION

The imminent advent of satellite astronomy from orbiting observatories free from the obscuring and distorting effects of the earth's atmosphere will undoubtedly bring about a major revolution in astronomy. The rapidity of its impact will depend on how quickly sophisticated instrumentation can be developed to take full advantage of the full capabilities of large telescopes located on stable platforms outside the earth's atmosphere.

This report is concerned with a special but vital aspect of the instrumentation problem; namely, with the image tube which serves the function of converting an optical image formed by the telescope or its spectrograph into an electrical signal which can be transmitted to earth. Such signal conversion functions can be performed for one picture element at a time, of course, by a photomultiplier which is a well-developed, reliable device even under the rigors of satellite service. However, data acquisition, one picture element at a time, is far too slow for most of the astronomical work that is to be done from an orbiting observatory, and, while the photomultiplier has a high degree of usefulness for certain kinds of observations, realization of the full potential of satellite astronomy hinges upon development of suitable image storing and transmitting instrumentation. It should be pointed out that the term "image storing and transmitting instrumentation" includes a wide range of possible techniques, among which may be mentioned the use of photographic plates, thermoplastic recording tapes, Xerographic processes, color center production in insulators, thermoluminescence, and the various photoelectric and photoconductive television pickup or camera tubes and related tubes that have been modified to give long image integration and storage times coupled with slow scan readout appropriate to astronomical applications. The possibility of returning one or more data capsules to earth from an orbiting observatory has not been ruled out in making up this list, although every one of the techniques mentioned is capable of being handled by remote manipulation and its stored data extracted in the form of an electrical video signal that can be telemetered back to earth. All of the image recording media mentioned are reuseable except the photographic film or plate.

It is not the intent of this report to attempt to select the "best" method of handling the problem of converting the optical image to an electric signal or alternatively of getting the stored data back to earth in a recoverable capsule. It is rather to attempt to define the performance requirements that must be met by an image converter (this term being used henceforth in the broadest sense) in various kinds of service, i.e., in use in various classes of observations that can be performed to advantage from an orbiting observatory, and, in the light of these performance requirements, to see which of the techniques known at present appear to have promise of meeting the requirements now or after further development.

There is a very good reason for beginning early to give serious thought to image converters for use in advanced-generation orbiting observatories that will be launched a number of years hence. Image conversion instrumentation is already under development for the first three NASA orbiting astronomical observatories; the S-18 series constituting the first-generation OAO's and similar instrumentation will perhaps be used for later satellites of similar design and degree of sophistication. We are attempting here to foresee needs beyond the instrumentation now under development and to plan for image converters that will be needed between five and ten years from now. In view of the slowness with which photoelectric image tube development has proceeded in the past (development of all photoelectric devices has proved difficult and slow), a lead time of five to ten years for photoelectric image tubes that can meet the more stringent requirements of future satellite astronomy is certainly not unreasonable; it may even prove somewhat optimistic. As for other methods, only photographic ones are likely to need relatively short development time.

2. ASTRONOMICAL ASPECTS

From the astronomer's point of view, satellite astronomy offers three advantages over terrestrial astronomy: (1) it is free from atmospheric absorption, (2) it is free from atmospheric distortion of all kinds, and (3) it offers full use of a telescope in a synchronous orbit on virtually a 24-hour, daily basis.

Freedom from atmospheric absorption is the feature of an orbiting telescope that is of most immediate interest, for it will permit extension of observations into regions of the spectrum completely inaccessible to ground-based instruments and will greatly simplify observations in other regions, such as the infrared, that are not quite opaque from the ground but which are overlaid with atmospheric features that tend to obscure or complicate the observational details of interest. The most exciting and in many ways the most significant discoveries await exploration of the ultraviolet region of the spectrum below the atmospheric absorption cutoff at about 3000 Å down to about 912 Å. Below this wavelength, continuum absorption of interstellar atomic hydrogen will erect a virtually opaque screen that can be penetrated a little only by radiation from a few nearest stars. This opacity continues down into the soft X-ray region to about 50 Å, so there is little that can be observed in the region $\sim$50 to 912 Å. Within the range 912 Å to 3000 Å lie the resonance lines of most of the light elements of astrophysical interest as well as resonance lines of many of the heavier elements in states of high ionization, and this fact accounts for much of the astronomical importance of this spectral region.

With no turbulent, distorting atmosphere between telescope and star or planet, the principal barrier to greatly improved resolution for a large telescope is removed, and it appears quite likely that within a decade telescopes can be orbited which can attain over-all angular resolution for telescope plus guidance system better than 0.1 second of arc, an order of magnitude smaller than the value ordinarily attained terrestrially. Such an improvement in resolution has very significant consequences. With an instrument having 0.1-second resolution, the stellar image is concentrated into an area one hundred times smaller on the image receiver than it is in a terrestrial telescope limited by "seeing" to about 1-second resolution. If a resolution element of the detector of such a high-resolution instrument is just filled by the stellar image, contrast between star image and sky background is heightened by a factor 10, which is to say by 2.5 magnitudes, as compared with the seeing-limited telescope. Absence of atmospheric scattering and airglow at satellite altitudes gives a further reduction in sky background of somewhat more than one magnitude, thereby adding 0.5 magnitude to the instrument threshold.[1]

(1) See, for example, the article by W. A. Baum in "Astronomical Techniques," Edited by W. A. Hiltner, University of Chicago Press, Chicago, 1962, p. 8.

Thus an extension of the threshold of a large telescope by 3 magnitudes can be realized from removal of atmospheric distortion and airglow alone. This is equivalent to a 16-fold increase in primary mirror diameter, and, since we are talking about mirrors of at least 50-inch diameter (i.e., those whose diffraction-limited resolution in the visible region of the spectrum is $\lesssim 0.''1$), a 16-fold increase in effective diameter puts the limiting magnitude of such an instrument on a par with at least an 800-inch terrestrial instrument! On this basis alone, the limiting photographic magnitude of a 50-inch orbiting telescope with $0.''1$ resolution would be at least 25.7 as compared with 23.7 for the 200-inch Hale telescope.(1) As we shall see (Appendix A), the limiting magnitude of a telescope equipped with an ideal image tube having a photocathode with a quantum efficiency of 10% is approximately 2.5 magnitudes better than it is with 103a-O plates provided both give the same resolution. Therefore, our 50-inch orbiting instrument equipped with a suitable image tube would reach an incredible (by present standards) 28th magnitude with the same exposure the 200-inch Hale telescope requires to reach 23.7 magnitudes with 103a-O plates. (Actually, the magnitude attainable with a "noiseless" image tube is limited only by its storage capacity, and the comparison being made here assumes a storage capacity at least equal to that of the 103a-O plate.) Fluctuations in the mean sky background introduce an additional source of "noise" not accounted for in these estimates, as was pointed out recently by Miller,(2) and these fluctuations may limit the threshold to about 26 magnitudes which is still quite an advance over present terrestrial thresholds. Moreover, at a threshold of 25 to 26 magnitudes, galactic counts are capable of giving an accurate, unambiguous value for the radius of curvature of the Universe independent of any identification of the red shift with a recession velocity.(3) This might well be the most important single result that can be obtained by working to threshold with a large orbiting telescope.

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(2) R. H. Miller, "A Limitation of Photometry of Faint Objects," a paper read before the 113th Meeting of the American Astronomical Society, Tucson, April 1963.

(3) A. R. Sandage, Conf. on Quantitative Spectroscopy and Selected Applications in Space Science, California Institute of Technology, Pasadena, March 1963.

In addition to advantages in stellar astronomy that stem from a ten-fold increase in resolution, there are equally important gains to be had in studying extended objects: planets, gaseous nebulae, resolution of individual stars in galaxies, etc. The obvious advantage here is the acquisition of finer detail, but the increased ability to distinguish small contrast differences plays an equally important role.

Bearing in mind that the specifications of image conversion equipment should allow the fullest possible realization of the potential advantages of an orbiting telescope over an earth-based instrument, it is possible, as will be shown, to satisfy these requirements with three classes of converters distinguished by their linear resolution. The first class is trivial for the present discussion; it is characterized by tubes having a single resolution element of macroscopic size and typified by the familiar photomultiplier tube. For observations of a kind for which a photomultiplier is the preferred terrestrial instrument, it will also be a satisfactory instrument in an orbiting observatory. Examples of such observations are photometric magnitude and color index measurements of single objects, determinations of light curves of variables and eclipsing binaries, measurements of interstellar polarization, etc. It may be that the future role of the photomultiplier in space astronomy is limited even for these latter measurements, however. The development of image tubes having wide dynamic range and good photometric accuracy will eventually largely displace the less versatile photomultiplier in satellite observatories.

Turning to the true image converters, they fall, in terms of resolution required of them, into two general classes: low and high resolution. The low-resolution class encompasses a range of linear resolutions roughly from 10 to 40 line pairs per millimeter (lp/mm) with ~ 20 being a fair average figure. This group includes a wide variety of image tubes and TV camera tubes in existence today. The high-resolution class, on the other hand, encompasses a range of linear resolution that is characteristic of the photographic plate which is itself a candidate for this application. Linear resolutions of 50 to 130 lp/mm or even higher are the realm of this class of image converters with a fair average figure being taken as 100 lp/mm, a value characteristic of the Type III plate.

The case for development of high resolution image converters deserves further comment. We shall consider both technical and economic aspects of image converter resolution. There is a strong technical reason favoring the high resolution device for only a few types of observation. As an example, consider work that requires direct imaging at wavelengths shorter than about 1200 Å down to the limit 912 Å at the onset of Lyman continuum absorption. When work in this region involves faint objects, it must generally be carried out with an image tube at the prime focus of the telescope because the reflectivities of all presently known materials fall to low values ($\lesssim 18\%$) below about 1200 Å and the light loss caused by reflection at the secondary mirror of a Cassegranian telescope might well be unacceptable. When an image tube is used at the prime focus, the scale factor at the prime focus being necessarily large for a compact satellite telescope, it is essential that an image receiver of high linear resolution be used if acceptable angular resolution is to be realized for the entire system. A more common example of a need for high resolution image converters is to be found in spectroscopic work requiring high spectral resolution. For instance, measurement of velocities in binaries, determinations of radial velocities of stellar objects when these velocities are small, and measurement of spectral line profiles are a few well-known classes of observations in which spectral resolutions of the order of 0.01 Å are required. Because of the very great difficulties encountered in building light weight, high dispersion spectrographs that can maintain accurate alignment through the rigors of rocket launching, it is unlikely that spectrographs having reciprocal dispersions better than about one Angstrom per millimeter even in second or third order will find use in orbiting observatories. Consequently, satellite spectrographs must be used with very high resolution image converters to achieve spectral resolutions of the order of a few hundredths of an Angstrom. Echelle spectrographs offer an alternative way to do high resolution spectroscopy with a low resolution image tube but at the expense of added complications because predispersers are required to prevent overlapping orders due to the narrow free spectral range covered by Echelle instruments. The same disadvantage is present to a lesser degree in a regular grating spectrograph used at higher grating orders. This case is typical of several in which the high resolution image converter offers a straightforward solution to an instrumentation problem that could perhaps be handled differently using a low resolution device but at a penalty in performance, convenience, or size and weight.

If no other arguments than those above in favor of the high resolution converter could be presented, there is some question whether the effort needed to develop such instruments could be justified. There is, however, an economic argument that favors high resolution converters quite strongly for some common types of observational work. Basically, the argument rests on the fact that the rate of acquisition of useful astronomical data by an orbiting telescope depends markedly upon the resolution of its associated image converter, to such an extent that a moderate improvement in resolution could permit one orbiting observatory to do the work of two in certain cases. Under these circumstances a sizeable program to improve image tube resolution would be economically justified. This point is sufficiently important to warrant detailed consideration.

First, the useful diameter of an image converter is limited, quite aside from tube construction problems, by the principal residual aberration near the axis in a parabolic mirror telescope, namely, coma. Correctors (e. g., Schmidt or Ross correctors) can improve off-axis performance in some spectral regions, and where these can be used successfully the image converter may in principle be made large in size with relatively low resolution rather than small with high resolution to achieve the equal total numbers of picture elements and equivalent data acquisition rates.

However, over sizeable regions of the far ultraviolet spectrum that will be of particular interest for satellite astronomy, the use of correctors based upon transmission optics is impractical. The useful size of the field of an uncorrected paraboloid may somewhat arbitrarily, but reasonably, be taken as the distance off-axis at which the size of the comatic image of a point source equals the size of the diffraction pattern of the source. Appendix D discusses the limitation on telescope field and on image tube diameter due to coma under the condition that the telescope focal length be as long as necessary to match image tube resolution to telescope resolution. For example, a 50-inch paraboloid has a coma-limited field of about 1 inch, but its effective focal length would have to be about 400 feet to match its resolution to that of a low-resolution image tube (20 lp/mm) in visible light and the corresponding focal ratio would be f/100.

A major disadvantage in having to work at such large f-ratios is that the time required to reach a given magnitude increases as f^2 (see Appendix A, Eqs. A-10 and A-15); thus a low resolution tube (δ = .005 cm) requires 25 times as long to reach a given magnitude as a high resolution tube with δ = .001 cm. Moreover, the difference in rate of acquisition of information between these two tubes is larger still by another factor 25, assuming both tubes have the same size photosurfaces. This is because the number of picture elements per picture is proportional to δ^{-2}, and the number of exposures per unit time to a given magnitude also varies as δ^{-2}. This is because we require that $f = \delta/\lambda$ to match telescope and image tube resolutions, and exposure time is proportional to f^2. Consequently, the rate of acquisition of astronomical information varies as δ^{-4}, or a factor 625 in favor of a high resolution tube (100 lp/mm) over one with one-fifth as much resolution (20 lp/mm). The "rate of acquisition of astronomical information" as used here refers to the number of picture elements scanned per second which could contain observable stars brighter than a given magnitude. This is by no means the only way the data acquisition rate may be sensibly defined, and other definitions may give a different dependence on δ. However, the above definition does make sense for much work in which a two-dimensional star field must be viewed.

The telemetry bandwidth required to transmit the data is proportional to the data acquisition rate, that is, to δ^{-4}. A 1 megacycle/sec bandwidth can handle 2×10^6 binary bits per second. To achieve 3% photometric accuracy (ϵ = .03), 5 bits per picture element must be reserved to transmit intensity information giving a capacity of 4×10^5 picture elements per second. A square picture having 630 elements on a side (1260 TV lines) could thus be transmitted through a 1 mc channel in 1 second together with enough intensity information to give ϵ = .03. A 2500 line picture would take about 15 seconds to transmit, and so on, the transmission time per picture being proportional to the square of the number of lines in it.

A high resolution image tube that can resolve 100 lp/mm over a 1" dia. face would handle a picture corresponding with 5000 TV lines and four minutes would be required to transmit it over a 1 megacycle/sec channel. Therefore, the capacity of a telemetry channel of 1 mc/sec bandwidth will not begin to limit the data handling capacity of a 50" telescope with a high resolution image tube as long as one is exposing to reach at least ~ 19th magnitude (see Appendix A). For such an instrument and telemetry system then, 19th magnitude becomes a rough dividing line: when exposures are shortened to reach stars brighter than 19th magnitude, not all of the information acquired by the telescope and image tube can be transmitted by the data link. However, when exposing for fainter objects, the full data acquisition capability of telescope and image tube can be realized. This dividing line appears at lower and lower magnitudes as the telemetry bandwidth increases. The critical dividing magnitude may be found roughly from the expression 19 - 2.5 log B where B is the bandwidth in megacycles per second. Bandwidths of the order of 20-30 mc/sec push the dividing line down to around 16th magnitude, and eventually laser communications will do much better still, until scarcely any serious work will be done to such small magnitudes that the data transmission rate would become a limiting factor. The point of this discussion is that when exposing for objects fainter than the critical magnitude (and such cases occupy an increasingly large proportion of all work as the telemetry bandwidth increases), the overall data acquisition rate varies with the fourth power of the linear resolution of the image tube expressed in line pairs per mm or as δ^{-4} in terms of the δ of a resolution element. In such a case it is true that a mere 20% increase in resolution of the image tube serves to double the overall data acquisition rate. This is the basis for the earlier statement that in favorable cases a moderate improvement in image tube resolution could enable one orbiting observatory to do the work of two.

3. SOME TECHNICAL ASPECTS OF VARIOUS APPROACHES TO ASTRONOMICAL IMAGE CONVERSION

In the foregoing discussion we have usually referred to image converters as image tubes for convenience, although we took pains initially to make it clear that image conversion in the broad sense would be the general topic of this report. The word "tube", however, was not used solely as a matter of convenience or as a concession to common usage since, as will be seen subsequently, the recoverable photographic plate appears to be the only non-vacuum tube image converter that merits consideration at present, and even it appears best adapted to the role of a recorder and storer of information from another image tube. We shall now consider certain good and bad features of several ways in which astronomical image conversion in its broad sense may be carried out in an orbiting observatory.

The basic input to our system consists of light collected by the associated telescope, and this light may either be recorded directly by detecting some irreversible process that a photon induces in the primary receiving surface of the image converter, or it may be recorded indirectly by detecting the products of the initial action of light on the primary receiver. The chief example of the first alternative is, of course, the photographic emulsion used to record a light image directly. Unfortunately, even the fastest emulsions that have been made have relatively low quantum efficiencies and therefore are overly wasteful of the incident light when faint objects are to be studied. The photographic emulsion, furthermore, requires some form of subsequent processing either in the satellite observatory or after return to earth, and the emulsion is not reuseable. Against these disadvantages must be considered the advantages of high resolution and large storage capacity of modern emulsions. Even the fastest available emulsions with comparatively low resolution still outstrip the best existing signal generating photoelectric image devices in this respect. In the matter of spectral response photographic emulsions can also compete successfully with photoelectric tubes. In linearity and dynamic range, the photoelectric device is potentially much superior to the emulsion, but this superiority is far from being fully realized in photoelectric tubes that have been developed so far.

Probably the most potent use of the photographic emulsion in an orbiting observatory is as a recorder of photoelectrons from a photoemissive surface, and this use of photographic emulsions will be discussed subsequently.

Turning next to indirect methods of light recording, almost all of these involve conversion of light into electric signals of some kind. The principal exception is the Baird Evaporagraph in which light energy absorbed in a thin liquid film heats it locally and causes a change in film thickness by evaporation. Variations in film thickness corresponding with the light image may then be observed by interference methods. The efficiencies of thermal conversion devices of this kind are inherently low because the absorbed energy is rapidly shared by a sizeable number of atoms or molecules of the radiation receiver, and the dissipation of energy from the site of initial absorption is sufficiently rapid that its concentration quickly falls below that necessary to produce a detectable change in the receiver, e. g., by evaporating molecules in the case of the device mentioned. For this reason we confine our attention to processes in solids in which the energy of an absorbed photon is promptly delivered to one or at most a small number of charge carriers (electrons and/or holes) in the solid. In this case the recipients of the photon energy each receive a large enough energy increment to render them detectable in principle, at least for a short time until they dissipate their excess energy. Specifically, the photoelectric effect in solids possesses these properties. The absorption of a photon by the valence electrons in the solid excites a single electron into the conduction band of the solid where it (or the hole created in the valence band by loss of the electron) can in principle be detected by accelerating it with an electric field either to an external electrical conductor (photoconductivity) or to an external electrode which the conduction electron reaches by leaving the solid (photoemission).

Photoconductive processes are characterized by high inherent quantum efficiency ($\gamma \approx 1$) because nearly every incident photon that is not reflected at the surface of the solid excites an electron into the conduction band of the solid when it is absorbed. The conduction electrons thus produced are immediately fair game for several energy-robbing processes that can prevent them from moving far enough in the solid to be detected, but in many cases the overall efficiency of the whole process, including detection in an external circuit, can be made rather close to unity. For reasons that are not yet clearly understood, the efficiency of the photoemissive process is not nearly as high as it can be for photoconductivity; maximum values of γ as high as 35-40% have been observed on occasion in the laboratory in certain of the multialkali photocathodes, but values between 10% and 20% are more characteristic. The difference in γ between photoemissive and photoconductive detection amounts to about one magnitude advantage in limiting magnitude in favor of photoconductive detection (see Appendix A), but the limiting magnitude can be reached in one fifth to one tenth the time, since τ_o varies as γ^{-1}, with a photoconductor. Such a reduction in τ_o is a very significant factor as it yields a corresponding increase in the data acquisition rate.

Ideally then, the photoconductive process is capable of detecting virtually every absorbed photon, and from an efficiency standpoint it approaches the ultimate in detection methods. At present, however, photoconductive image converters, exemplified by the Vidicon, have fallen far short of their potential in this respect. In fact, photoconductive image tubes are at present orders of magnitude less sensitive than photoemissive tubes. The choice of photoconductive materials for image tubes has been severely limited by the requirements set by commercial television to which development of such image tubes has been tied. It is recommended that the potential of photoconductive tubes be studied further with the requirements of astronomy in mind. When long signal integration and storage times are of interest, as they are in most astronomical applications, higher resistivity photoconductors can be used, and these are far more numerous than the very limited number available for commercial television camera tubes where a frame time of 1/30 second dictates the resistivity of the material. With a greater number and variety of materials to consider, it is not unlikely that a tube can be designed and developed which will be able to exploit the potentially high quantum efficiency that many photoconductors possess.

We consider next the largest and most varied group of image conversion devices, the photoemissive tubes. These, as a group, stand ahead of all others presently available in respect to sensitivity, and with the exception of the photographic film certain of the photoemissive tubes are capable of the highest resolution. In photometric linearity and dynamic range we also find that certain members of this class of converters excel all others. While none of the photoemissive devices nor any other present converter possesses to a sufficient degree all of the performance features that we seek for advanced generation OAO's, some of the existing photoemissive designs meet minimum performance requirements in many respects.

The Image Orthicon, C. P. S. Emitron and their several modifications and improvements represent the most advanced state of the art in signal generating image tubes. Recent development of improved thin film targets such as MgO and low density KCl smoke for the image orthicon has increased the signal integration time for such tubes to the order of 15-30 minutes, and it appears likely that still longer integration times will eventually be possible. In regard to resolution, it is well known that maximum resolution in tubes such as the image orthicon occurs at light intensities just below the "knee" of the characteristic curve. This knee represents the maximum photocathode illumination at which the output of the tube is still a reasonably linear function of light intensity. Thus maximum resolution is obtained at maximum useable (linear) photocathode illumination, and the resolution decreases at lower light intensities to roughly 10% maximum when the light level approaches the threshold for the tube. Resolutions as high as ~ 600 lp/mm have been obtained[4] in the central region of the sensitive area of laboratory image orthicons. Such resolutions have only been obtained so far at relatively short frame times ($\leq$ 1 sec) where lateral leakage in the image orthicon target does not begin to limit resolution. Boerio and Goetze[5] have found that low density KCl smoke targets possess extraordinarily low lateral leakage, and it is likely that tubes with such targets will be capable of resolutions of the order of 50-60 lp/mm with much longer image integration times than 1 second.

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(4) J. A. Hall and H. Shabanowitz, ARL Report #154, Aeronautical Research Laboratory, Wright-Patterson AFB, (Dec. 1961) p. 38.

(5) A. H. Boerio and G. W. Goetze, Scientific Paper 62-112-252-P3, Westinghouse Research Labs., Pittsburgh, Pa..
See also G. W. Goetze, Adv. in Electronics and Electron Physics, XVI, p. 145, Academic Press, N. Y. (1962).

The problem of decreasing resolution at lower light levels in the image orthicon remains, however. This loss of resolution at lower light levels is a consequence of reduction in signal-to-noise ratio. It is more severe when the tube noise is high, but the effect eventually appears even in an ideal, noise-free image tube as a result of the discrete nature of the incident light. In this case the resolution deteriorates so δ is proportional to $n^{-1/2}$ where n is the average number of photons per unit area incident on the photocathode during a fixed exposure time. If one wishes to image a scene having a large dynamic range, only the high-light areas will show good resolution. Such effects are particularly annoying in spectroscopic work, especially in high resolution, line profile studies.

The origin of the decrease in resolution with illumination in actual image orthicons lies in the noise inherent in the method whereby potential variations on the surface of the thin film target in the image orthicon corresponding to the light image are converted into a video signal by an electron beam that scans the target surface once each frame time. Analysis shows that in astronomical applications which permit slow scan readout of the picture and allow subsequent recharging of the target to its original potential (corresponding to erasure of the previous image) by other means than the reading beam itself, a considerable improvement in signal-to-noise ratio results, and this has the practical effect of maintaining resolution at its maximum value over much wider brightness range.

Present signal generating tubes depend for signal readout upon a scanning electron beam which reads a surface potential map resulting from charging a surface with photoelectrons suitably imaged by an electron optical system or by electrons making up an intensified electron image of the photo-emission pattern. When the image contrast is extreme, as it often is for stellar images against a dark sky, certain characteristic errors are introduced into the transduced picture that originate in redistribution of secondary emission from the storage target of the tube and in lateral bending of the reading electron beam by potential gradients parallel to the target surface at the edges of regions corresponding to large differences in image brightness. These effects are always present to some degree in conventional signal generating tubes, although they can be controlled to some extent by careful tube design and choice of operating conditions for the tube. Both effects are most serious in high resolution spectroscopy, particularly in the study of spectral line profiles, and in direct imaging of close double stars. The transmission secondary emission target with back-side mesh[6] with signal integration and readout carried out sequentially rather than simultaneously offers what appears to be the best means of overcoming redistribution errors in a high contrast image. Beam bending can be reduced by increasing the strength of the axial magnetic field in which the tube operates. In fact, if one can go to the extreme of using a superconducting solenoid with a tube having the kind of target described and derive the reading beam from a photosurface scanned by a monochromatic, microscopic light spot rather than from a thermionic cathode, it is likely that a considerable improvement in performance for astronomical images would result. A detailed analysis of the characteristics of such a device will be the subject of a forthcoming report.

It still remains to be seen whether or not the inherent defects of present day signal generating tubes can be overcome by unconventional

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(6) G. W. Goetze, loc. cit.

techniques that may be applied when one is not bound by commercial television requirements, but it is clear that a great deal of exploration remains to be done along these lines with much room still left for inventiveness and ingenuity.

We turn next to the electronographic image converters, the prototype of which is the well-known Lallemand tube. This class of converters images, by electron optical means, a photoelectric image directly upon a photographic emulsion which records the passage of each electron (after it has been sufficiently accelerated) by one or more blackened silver grains when the plate is developed. In principle, and often in fact, this type of tube is the simplest of all, and by some fortunate negation of Parkinson's law it also turns out to be capable of the best performance in most astronomical applications. Resolutions as high as 70 lp/mm[7] have already been achieved, and this is by no means the limit. A magnetically focused tube in a 20 kilogauss superconducting solenoid would have a fundamental resolution limit (set by transverse photoelectron velocity) of at least 200 lp/mm in the visible and more than half that over most of the ultraviolet (with a suitable high work function photocathode). Even electrostatically focused tubes are probably capable of better than 100 lp/mm in the visible spectrum at the present state of the art. In linearity the electronographic converter is outstanding as long as one is willing to count individual electron tracks; problems in linearity only become evident when one exposes enough to allow use of a densitometer for convenience. Even when photometry is determined with a densitometer, the characteristic curve for this process is linear to the chemical fog level of the plate because reciprocity effects that contribute to curvature at the toe of the H & D curve for the emulsion used as a light receiver are absent when it records fast electrons.

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(7) W. A. Hiltner, private communication

There would be little point in mentioning electronographic image converters in connection with orbiting observatories were it not increasingly evident that within the next decade it will be feasible to recover film records from an orbiting observatory, and if electronographic image conversion maintains its present superiority over signal generating instrumentation, it is likely that OAO's can and will be built to provide recovery of one or more film packages. In its ability to store information compactly the fine grain film probably has no peer. Its information storage capacity is so great that the information transmission rate limitation that we discussed earlier in connection with data acquisition rates would never arise. The recoverable film, in short, provides a virtually infinite bandwidth medium for transmission of data from satellite to earth, and it may well provide less ambiguity and noise than any conventional form of telemetry. An alternative to film recovery would be on-board processing followed by reading of the film by means of flying spot scanning with real time telemetry of the resultant video signal. In this case, however, the limitations set by telemetry bandwidth upon data acquisition rate would still apply.

Several forms of electronographic image tubes are under development for terrestrial astronomical use; however, no serious thought appears to have been given to the form such a tube should take for use in an orbiting observatory. Now that the recoverable data package appears to be a good prospect for the 1970's, it is recommended that design and development of electronographic image converters for OAO application begin without delay and that such a development program parallel that of the signal generating tubes.

IV. CONCLUSIONS

The major part of this report has been concerned with establishing a minimal set of performance requirements for a useful OAO image converter. These may be summarized as follows:

1. Resolution $\gtrsim$ 20 line pairs/mm over at least a 1-1/2" diameter sensitive area. Data acquisition rate depends very strongly upon resolution. Resolutions as high as 100 lp/mm needed in certain types of work.

2. Sensitivity should permit recording every photoelectron if full advantage is to be taken of the quantum efficiency of the photosensitive surface. Noise generated in the tube beyond the photosurface should not obscure the information contained in the primary photoelectric signal.

3. Photometric accuracy and linearity should be at least good enough to reproduce a 30-step gray scale which is equivalent to a 3% photometric accuracy.

4. Exposure integration time must be at least of the order of 15-30 minutes and times of the order of several hours should be the eventual goal. Readout should generally take place after exposure is complete, and readout times should be appreciably shorter than exposure times. Readout time will usually be determined by the available telemetry bandwidth. Real time transmission rather than intermediate storage is much preferred because the large amount of information per picture places severe demands upon the capacity of an intermediate storage stage.

5. Stability is established by the requirements on resolution and photometric accuracy. That is, the image must not shift or distort locally by more than about half a resolution element ($\lesssim$ .02 mm) over periods

comparable with the longest exposure times likely to be used, and the sensitivity of the photosurface should not vary by more than ~ 1% during such periods. The gain of the readout system must also be stable to the same degree.

6. Spectral response should extend as uniformly as possible from ~ 900 Å through the visible into the near infrared. At present it is not possible to achieve such a range with a single photosurface, but the final OAO system should provide such coverage using two or more tubes if necessary. Particular emphasis should fall upon achieving good sensitivity in the range ~ 900 to 3000 Å. Fluorescent conversion using sodium salicylate has been found to be practical in this wavelength region.

7. Uniformity of response over the area of the light sensitive surface should ideally be in keeping with the photometric accuracy sought, i. e., ~ 1 to 2%. However, a smoothly varying response differing by as much as ~ 20% over the surface might be tolerated if the contours of constant sensitivity are simple in shape to allow the final data to be corrected for sensitivity variations.

It may be stated categorically that no existing image converter can meet all of the above performance requirements. Of the signal-generating tubes those that are modifications of the image orthicon and incorporate one or two stages of either cascade phosphor-photocathode or transmission secondary emission image intensification and use a low leakage KCl smoke or MgO storage target have shown the best performance to date, but even these highly complex tubes fall short of OAO requirements in several respects. The outlook for successful development of a tube along these lines must be rated as only fair. The inherent complexities of such devices work against them. A rather long and costly program of research and development will probably be needed, and it will be necessary for those engaged in this work to free themselves from thinking in terms of television requirements. Many of the electron optic problems encountered in present signal generating tubes, including such troublesome features as redistribution and beam-bending, could be eliminated through the use of strong magnetic focusing with solenoidal fields in the 10 to 30 kilogauss range produced by superconducting solenoids.

The photoconductive signal generating tubes probably stand to gain most from designs that take advantage of the unusual environmental and operational conditions that can be established in an orbiting observatory. Such tubes are inherently somewhat simpler than the photoemissive signal generating tubes, and as a rule photoconductive tubes have been capable of higher linear resolution than photoemissive tubes. In many cases the resolution limit of photoconductive image tubes seems to be in the size of the reading electron beam rather than in the properties of the photosurface. Again, development of an astronomical image converter of this kind can benefit from dissociation from TV requirements which severely limit the choice of photoconducting materials.

Finally, non signal-generating tubes of the electronographic type have entered the picture in view of the probable development of recoverable data capsules. Such tubes come closer than any others to fulfilling OAO requirements at present, but problems still remain in such matters as remote film handling and film storage, preservation of the photocathode for periods of a year or more, long term stability, further increase in resolution, etc. Again strong magnetic focusing deserves consideration as a means of avoiding certain electron optical problems and as a means of avoiding loss of resolution when a thin window (Lenard window) is used to prevent outgassing products from the film from harming the photocathode.

If one could be sure that film recovery would be feasible from early models of the advanced-generation (post S-18 series) OAO's, first priority should probably go to development of suitable electronographic image converters. Otherwise, signal generating tubes will have to be employed in the interim, and priority should go to the photoemissive types with a parallel research program at a more modest level to explore more fully the potential capabilities of photoconductive types. At the same time a long range program should be initiated which is aimed at making electronographic converters available when data capsule recovery becomes practical.

APPENDIX A

Limiting Magnitude for a Diffraction-Limited Telescope used with an Image Converter

(1) Nomenclature

n = number of photons/cm^2-sec. incident on the telescope objective from a star

N = number of photons/cm^2-sec.-stearadian incident on a telescope from sky

t = image integration time in seconds

γ = quantum efficiency of image converter, number of output events per incident photon

α = angular resolution of telescope, radians. We take $\alpha = \lambda/D$ where λ is the wavelength of light, cm.

D = telescope aperture, cm

F = telescope focal length, cm

f = focal ratio, F/D

m = magnitude of star

M = sky magnitude per stearadian = -4.4 for terrestrial instrument ≈ -3.4 for orbiting instrument.

S = signal from star in events per second per resolution element at the image converter output.

B = background events per second per resolution element at the converter output.

k = coefficient of recognition or the minimum signal-to-noise ratio at the converter output that permits a chosen probability of detection of signal against background. Baum [1] takes $k = 5$ as insuring reliable detectability (> 90%) of stellar images.

β = average number of background events originating in the image converter per second per cm^2 of photosensitive surface.

δ = diameter of a resolution element of the telescope at the photosensitive surface of the converter in cm. We assume the telescope focal length has been chosen to match the angular resolution of the telescope to the linear resolution of the image converter so $\delta = \alpha F$.

S_o = least detectable, or threshold, signal

C_o = least detectable contrast, S_o/B

R = ratio of instrumental to sky backgrounds

$$= \frac{\beta \delta^2}{N \alpha^2 D^2 \gamma}$$

E = image tube storage capacity in events per cm^2 referred to the photosensitive surface.

ϵ = photometric accuracy

We neglect all factors $\frac{\pi}{4}$ in the following discussion.

(2) Limiting Magnitude

From the above definitions clearly,

$$S = n \gamma D^2 t \tag{A-1}$$

$$B = N D^2 \alpha^2 \gamma t + \beta \delta^2 t = N D^2 \alpha^2 (1 + R) \gamma t \tag{A-2}$$

Since the background events are random, it follows that the "noise" or fluctuation in B is proportional to $\sqrt{B}$. To this must be added fluctuations in S which at threshold is comparable with the signal from the sky background. We neglect this refinement here for simplicity, noting that in so doing we make no error of any consequence in the end results.

$$S_o = k \sqrt{B} \tag{A-3}$$

$$C_o = \frac{S_o}{B} = \frac{k}{\sqrt{B}} = \frac{k}{\alpha D \sqrt{N \gamma t (1 + R)}} \tag{A-4}$$

The magnitude, m_o, of a star at threshold is (by definition of magnitude)

$$m_o = M - 2.5 \log\left(\frac{n_o}{N}\right) \quad \text{(A-5)}$$

But $n_o = S_o / \gamma D^2 t$ so

$$\frac{n_o}{N} = C_o \, \alpha^2 \, (1 + R) \quad \text{(A-6)}$$

and from (4), (5), and (6)

$$m_o = M - 2.5 \log\left(\frac{\alpha k}{D}\right) - 1.25 \log\left(\frac{1 + R}{N \gamma t}\right) \quad \text{(A-7)}$$

(3) Time to reach limiting magnitude

If E is the storage capacity then the detector departs markedly from linearity (we will say it saturates) when E events/cm^2 have accumulated, and this is all the information that one can collect in a single exposure.

The exposure time, t_o, required to reach saturation is such that the star image signal $S(t_o)$ just saturates a resolution element of the tube, i. e.,

$$S(t_o) = \delta^2 \, E \quad \text{(A-8)}$$

Inserting equation (1) into (8) and using $\delta = \alpha F$ gives

$$t_o = \frac{E \alpha^2 f^2}{n \gamma} \quad \text{(A-9)}$$

It is convenient to eliminate n from this equation to get t_o in terms of the background N. This can be done with the aid of (2) and (3) giving

$$t_o = \frac{E^2 f^2 \delta^2}{k^2 N \gamma \; (1 + R)} \quad \text{(A-10)}$$

(4) Saturation-limited magnitude

The limiting magnitude, equation (7), can actually be extended until exposure time, t, reaches the saturation value given by (10) or

$$m_o = M - 2.5 \log\left(\frac{1 + R}{E}\right) - 5 \log k + 5 \log F \quad \text{(A-11)}$$

The latter equation expresses the fact that the limiting magnitude of a telescope in combination with a detector of finite capacity is a function of the focal length only and not of the aperture of the telescope. The aperture determines not m_o but the time, t_o, required to reach m_o, and it enters into the expression for t_o (Eqs. 9 and 10) through the focal ratio or f-number.

(5) Ideal (noiseless) image tube limit

Consider the case of a noiseless (R = 0) image converter. Eq. (11) then becomes using $\delta = \alpha F$[with k = 5, $\alpha = 5 \times 10^{-7}$ radians = 0.1 seconds of arc, and M = -3.4],

$$m_o = 24.6 + 2.5 \log (E\delta^2) \qquad \text{(A-12)}$$

where $E\delta^2$ is the number of events $S(t_o)$ required to saturate a resolution element of the image converter. Since $E\delta^2 \geq 1$ it follows that $m_o \geq 24.6$ for an orbiting telescope with 0."1 angular resolution (i.e., $D \geq 50$ inches)for visible light.

(6) Photometry

An image converter capable of 1% photometric accuracy would have to be able to store 10^4 events per resolution element since the fluctuation in number of these events is proportional to the square root of the total number and 1% accuracy implies $(E\delta^2)^{1/2} \leq .01\ (E\delta^2)$, or $E\delta^2 \geq 10^4$. In general if ϵ is the photometric accuracy,

$$E\delta^2 = \epsilon^{-2} \qquad \text{(A-13)}$$

and equation (12) becomes

$$m_o = 24.6 - 5 \log \epsilon \qquad \text{(A-14)}$$

If $\epsilon = .01$ then $m_o = 34.6$, and if $\epsilon = .03$ then $m_o = 32.2$.

(7) Exposure time to reach magnitude,m

To reach magnitude $m < m_o$ requires an exposure

$$t = t_o / \text{anti log } 0.4\,(m_o - m) \qquad \text{(A-15)}$$

The time t_o (Eq. 9) can be put into the following simple form, making use of $\delta = \alpha F$ and Eq. 13:

$$t_o = \frac{1}{D^2 \epsilon^2 \gamma n_o} \qquad \text{(A-16)}$$

where n_o is the photon flux from the threshold star of magnitude, m_o.

To evaluate Eq. 16 a relation between n_o and m_o is required. There seems to be no generally agreed upon conversion factor for a given spectral class star. We shall adopt a value $n = 3 \times 10^5$ photons/cm^2-sec for a star of solar class of zeroth visual magnitude. [This comes from the value of irradiance = 2.43×10^{-10} lumens/cm^2 for $m_v = 0$ star given by Allen* which corresponds to 10^6 photons/cm^2-sec for light of wavelength 5550 Å and roughly 1/3 as much for a blackbody whose temperature is 6000 °K.]

Taking $\epsilon = .03$ gives $m_o = 32.2$ from Eq. 14, so $n_o = 4 \times 10^{-8}$. For a 50" telescope and an image converter with $\gamma = .06$ (a reasonable average over the visible spectrum) will have $t_o \approx 1$ year (3×10^7 sec).

Taking $t_o = 3 \times 10^7$ sec in Eq. (15) one can reach

$m = 13.5$ in $t = 1$ sec.

$m = 18.5$ in 100 sec.

$m = 22.2$ in 1 hour

$m = 24.7$ in 10 hours

$m = 26.7$ in 24 hours

It is evident from these figures that an image converter must have a very long integration time if it is to reach appreciably beyond the 200 inch Hale telescope. An interesting feature of equations 14 - 16 is the effect of the photometric accuracy, ϵ, upon m_o, t_o and $t(m)$. To a considerable degree the long exposures needed to reach a given magnitude are the result of our choice of $\epsilon = .03$ in the calculated example. If one wishes merely to reach very faint stars without regard for photometry, the way to proceed is to choose E and δ so ϵ (by Eq. 13) is large, say 0.25. Then $m_o = 27.6$ and $t_o = 22$ minutes which is about 300 times less than the exposure to reach 27.6 magnitude with $\epsilon = .03$. Moreover, the storage capacity of the image converter need be far less for $\epsilon = .25$ than for $\epsilon = .03$. Clearly, a different set of image tube parameters is needed for precision photometric work than for recording faint objects.

(8) Variable parameter systems

Ordinarily E is a fixed parameter of a given image converter design. However, in converters having electron optical focusing it is possible to vary δ by defocusing and in this way (Eq. 13) to change ϵ at

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* C. W. Allen, "Astrophysical Quantities", Athlone Press (University of London), 1955.

will even though E is constant. It is necessary to maintain $\delta = \alpha F = \lambda F/D = \lambda f$ in varying ϵ by defocusing. Therefore either the focal length of the telescope must be varied with δ or the f-number must be changed by means of an iris diaphragm on the primary mirror to vary D. Either ϵF or ϵf must be kept constant while δ is changed. If this is done properly one has control over the photometric accuracy ϵ and thereby over m_o, t_o, and the time t(m) to reach magnitude m. The versatility of such a variable parameter system makes it attractive.

APPENDIX B. SPECTROSCOPY

(1) Nomenclature:

The same nomenclature listed in Appendix A will be used in the following discussion with the following additions:

T = spectrograph transmission, a function of λ generally but taken as constant here.

K = reciprocal dispersion of spectrograph in Å/cm.

$d\lambda$ = spectrograph wavelength resolution, Å.

$\Delta\lambda$ = width of spectrum, Å.

(2) Threshold of detectability

The spectrograph may be considered as a filter which transmits a fraction T of light entering it in wavelength range $d\lambda$ and delivers this light to a resolution element of width δ in the image converter. As a rule, in a properly designed system $K\delta \geq d\lambda$; that is, the wavelength resolution of the system should be set by the linear resolution of the image tube, not by the design of the spectrograph, and we shall assume that the spectrograph dispersion is chosen so its resolution matches that of the image converter giving $d\lambda = K\delta$. It will also be assumed that all of the light from the star image enters the spectrograph and that the spectrum is not widened but is delivered to the image tube with a width δ normal to the direction of dispersion. Under these assumptions we are dealing with an optimum condition and any relaxation of the assumptions will reduce the limiting magnitude from the value calculated below.

The total light from a stellar image that enters the spectrograph slit is $S = nD^2t$ as in Eq. (A-1). A fraction T of this gets through the instrument and is spread out to a wavelength range $\Delta\lambda$. A fraction $\frac{d\lambda}{\Delta\lambda}$ of this falls on area δ^2 of the image tube, assuming that light from the star is evenly distributed over wavelengths in the range $\Delta\lambda$. It is simple enough to insert a spectral energy distribution function but our assumption is not too bad for main sequence stars and it simplifies the discussion. We make the same assumption about the spectral distribution of sky background light. Therefore the "signal" in terms of photoevents per resolution element of the image tube is

$$S = D^2 n \gamma T \frac{d\lambda}{\Delta\lambda} t \qquad \text{(B-1)}$$

The "noise" consists of fluctuations in the total number of photoevents in time t from star, sky, and image tube itself. As before we assume that $n \approx N\alpha^2$, i.e., that near the threshold of detectability the numbers of events from star and sky are comparable. The noise is therefore $[\,nD^2\gamma t \frac{d\lambda}{\Delta\lambda}(2 + R')]$ where R' is the ratio of background generated within the image tube to sky background plus star image. Thus

$$R' = \frac{\beta\delta^2}{(n + N\alpha^2)D^2\gamma T\frac{d\lambda}{\Delta\lambda}} \approx \frac{\beta\delta^2\Delta\lambda}{2nD^2\gamma T d\lambda} = \frac{\beta\delta\Delta\lambda}{2nD^2\gamma KT}$$

$$= \frac{\Delta\lambda}{T d\lambda} R' \qquad \text{(B-2)}$$

Since $\frac{\Delta\lambda}{T d\lambda} >> 1$ the background generated in the image tube may not be negligible in spectroscopic work as it was in direct imaging. In fact, we shall see that it dominates the performance of the system for spectra of objects fainter than about 18-23 magnitude and introduces a form of reciprocity failure that is absent in photoelectric image converters used for direct imaging.

The criterion for detectability is, as before, that the signal to noise ratio at threshold must equal k. This, applied to Equations (B-1) and (B-2), gives

$$nt = \frac{(2 + R')k^2 \Delta\lambda}{D^2 \gamma T d\lambda} \qquad \text{(B-3)}$$

When $R' << 2$ this equation shows that nt is a constant for a given system and consequently there is perfect reciprocity. When R' approaches or exceeds 2 then, since R' is a function of n, reciprocity failure enters. When $R' >> 2$ Equation (B-3) may be written

$$n\sqrt{t} = \frac{k \delta \Delta \lambda \sqrt{\beta}}{D^2 \gamma T d \lambda} \qquad \text{(B-4)}$$

so $n\sqrt{t}$ is a constant for sufficiently faint spectra.

(3) Critical magnitude

Consider the critical magnitude at which $R' = 2$. Eq. (B-2) gives

$$n_c = \frac{\beta \delta^2 \Delta\lambda}{4 D^2 \gamma T d\lambda} \quad \text{at } R' = 2 \qquad \text{(B-5)}$$

We take $\Delta\lambda = 2000$ Å corresponding to the width of the visible spectrum, D = 125 cm (50" telescope), $\gamma = .06$, $T \approx .33$, a typical value for a spectrograph in the visible, and $\beta = 100$ photoelectrons/cm^2-sec. which means a dark current of 10^{-16} amps/cm^2 and represents a fairly typical value for the better present-day image tubes, cooled to dry ice temperatures. Under these conditions, $n_c \approx \frac{150\,\delta^2}{d\lambda}$. Using $n \approx 3 \times 10^5$ photons/sec-cm^2 as the flux from a 0th magnitude star, the critical magnitude, m_c, may be written

$$m_c \approx 8.4 + 2.5 \log (d\lambda) - 5 \log \delta \qquad \text{(B-6)}$$

For a low resolution tube $\delta \approx .005$ cm; for a high resolution tube $\delta \approx .001$ cm. Thus m_c varies with tube resolution between limits

$$m_c \approx 20.9 + 2.5 \log (d\lambda) \qquad \text{low resolution tube}$$

$$m_c \approx 23.4 + 2.5 \log (d\lambda) \qquad \text{high resolution tube} \qquad \text{(B-7)}$$

A low resolution spectrum for stellar classification might have $d\lambda \approx 1 - 2$ Å giving m_c between 21-22 magnitude for a low resolution image tube and m_c between 23.5 - 24.5 for a high resolution tube.

For measurement of line profiles and work requiring high resolution m_c is about 4 magnitudes less than the above figures. It is unlikely that K can be made appreciably smaller than 10 Å/cm even by using a grating in higher order, say 3rd or 4th, simply because of practical difficulties in getting long focal length spectrographs into orbiting observatories. With K = 10, δ = .005 cm we have $d\lambda$ = .05 Å for a low resolution image tube. For the high resolution tube $d\lambda \approx .01$ Å and these $d\lambda$'s are about 4 and 6 magnitudes, respectively, smaller than values given above for low resolution spectra. The critical magnitude is then about 18 with either type of image tube for high resolution spectroscopy; however, the high resolution image tube will give a five times better spectral resolution for the same m_c.

(4) Time to reach critical magnitude

From (B-3) and (B-5) the time t_c to reach m_c can be found:

$$t_c = \frac{16\, k^2}{\beta \delta^2} \qquad \text{(B-8)}$$

Taking k = 5, β = 100,

$$t_c \approx \frac{4}{\delta^2} \text{ seconds} \qquad \text{(B-9)}$$

Since δ ranges from .001 to .005,

$t_c \approx 45$ hours for a low resolution tube

$t_c \approx 46$ days for a high resolution tube

Clearly, there is little hope of reaching m_c in practice. Treating m_c as an effective limiting magnitude, the following table lists magnitudes attained with various exposures

$m \approx 8$	after t = 1 sec.
$m \approx 13$	after t = 100 sec.
$m \approx 17$	after t = 1 hour.

APPENDIX C: RESOLUTION AND STORAGE CAPACITY

It has been shown (Eq. A-13) that the product $E\delta^2$ depends only on the photometric accuracy required of an image converter. Inasmuch as the storage capacity of a given type of converter is subject to basic limitations, these determine δ for a desired ϵ. For $\epsilon = .03$, it is necessary to have $E\delta^2 \approx 1000$. The range of resolutions being considered here is $\delta = .001$ cm to $.005$ cm corresponding with 100 and 20 line pairs per mm respectively. Therefore E ranges from 4×10^7 cm^{-2} for a low resolution (20 lp/mm) image tube to 1×10^9 for a high resolution (100 lp/mm) tube with $\epsilon = .03$.

The fast photographic plate (e. g. 103a-0) typically has $E \approx 5 \times 10^6$ cm^{-2} and $\delta = .002$ cm giving $E\delta^2 \approx 20$. Thus this photographic plate is incapable of giving $\epsilon = .03$ considered as a photon counter. We would expect instead $\epsilon \approx 0.25$ or a gray scale having a 4:1 brightness range. Actually fast plates appear somewhat better than this in practice because the manner in which they are used photometrically involves integration of silver grains over many resolution elements and smoothes the statistical fluctuations of grain counts considerably, but such integration is equivalent to making δ larger and is therefore not in contradiction with our analysis.

A photoelectric image tube of the signal generating type stores photoelectrons capacitively between scans of the readout electron beam. Thus the capacitance of the storage target and the largest target voltage, V_{max}, that can be read with good linearity by the electron beam determine the storage capacity E. The least detectable voltage, V_{min}, should be smaller than V_{max} by a factor ϵ to insure a gray scale with ϵ^{-1} distinct steps, or

$$V_{min} = \epsilon \, V_{max} \tag{C-1}$$

Consider a storage target of thickness d cm and dielectric constant κ. The capacitance of a resolution element (area δ^2) is

$$C = 8.85 \times 10^{-14} \, \frac{\kappa\delta^2}{d} \text{ farads} \tag{C-2}$$

If the target has an internal gain G or is preceded by an image intensifier such that G electrons are stored for every photoelectron leaving the photocathode of the tube, there will be 1.6×10^{-19} coulombs stored per photoelectron. The storage capacity E in terms of photoelectrons per cm^2 is therefore

$$E = \frac{CV_{max}}{1.6 \times 10^{-19} G\delta^2} \tag{C-3}$$

Making use of (C-2) this becomes

$$E = 5.5 \times 10^5 \frac{\kappa V_{max}}{Gd} \qquad (C-4)$$

Consider first a tube of the image orthicon type with a MgO storage target. The dielectric constant is 9.8 and practical values of V_{max} and G are ~ 2 volts and ~ 10 respectively. Target thicknesses are of the order of 2500 Å. With these numbers E is of the order of 4×10^{10} which is too large. Excess storage capacity demands larger values of target capacitance, according to (C-3), and there is a limit to how much d can be reduced to increase C. In the case of MgO the required adjustment in capacitance is not possible.

Consider next the usual glass target: $\kappa \approx 4$, $G \approx 4$, $d \approx 25\mu$, $V_{max} \approx 2$. These figures give $E \approx 4 \times 10^8$ which would be suitable for a moderately high resolution ($\delta \approx .0015$ cm) tube if the lateral leakage in glass were not so large as to preclude long storage times.

Consider finally the low density NaCl "smoke" target* for which $\kappa \approx 1$, $G \approx 50$, $V_{max} \approx 10$, and $d \approx 25\mu$. With these numbers $E \approx 2 \times 10^7$ which is about right for $\epsilon = .03$. This target may be operated at lower gain and with smaller thickness so it is quite feasible by properly tailoring the fabrication of the target to obtain values of E in the desired range, $10^7 - 10^9$. Evidently of the three targets considered only the low density smoke target can cover the required range of E. The lateral leakage in this material is reported to be so small that storage times of several hours are possible at resolutions in the 20 - 30 lp/mm range. The storage capability at higher resolution (it is believed to be able to resolve > 70 lp/mm) is not yet known.

In order to satisfy Eq. (C-1) for a given ϵ and V_{max}, the latter being a parameter of the type of image tube and not subject to much variation, it is necessary to be able to read out a certain minimum potential V_{min}. In present day signal generating tubes V_{max} is the order of a few volts, and if $\epsilon = .01$ is the desired photometric accuracy, V_{min} must be of the order of a few tens of millivolts. Such potentials are readable without much difficulty with present techniques, at least at the upper end of the range. Below 10 or 20 mv problems appear which are due to the velocity distribution of the electron beam and to variations in work function over the surface of the target. For $\epsilon = .03$, V_{min} is about 0.1 volt and the readout process is straightforward with no special problems.

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* G. W. Goetze, "Advances in Electronics and Electron Physics" XVI, Academic Press, N. Y., 1962, p. 145.

APPENDIX D: COMA-LIMITED FIELD OF AN ORBITING TELESCOPE

The angular size of the comatic image of an uncorrected paraboloid or relative aperture f at an angular distance θ off-axis (both angles subtended at the telescope objective) is given approximately by

$$\phi = \frac{3\theta}{16 f^2} \tag{D-1}$$

For a telescope with a corrector (Schmidt, Ross, etc.), coma is reduced by a large factor, and (D-1) may be written

$$\phi = \frac{3c\theta}{16 f^2} \tag{D-2}$$

where c typically lies between 10^{-2} to 10^{-3}.

If D is the diameter of the sensitive area of an image tube, then $D \leq F\theta_{max}$. For a diffraction-limited telescope (see Appendix A), the resolution is approximately λ/D, and we shall arbitrarily, but reasonably, say that θ_{max} in (D-2) is determined by $\phi = \lambda/D$. Also, for such a telescope, $f = \delta/\lambda$ (Appendix A). Putting these relations into (D-2) gives

$$D \leq \frac{16\,\delta^3}{3\,c\,\lambda^2} \tag{D-3}$$

If ℓ is the number of TV lines in a picture of width D, then

$$\delta = \frac{D}{2\ell} \tag{D-4}$$

and Eq. (D-3) becomes

$$D^2 \geq \frac{3\,c\,\lambda^2\,\ell^3}{2} \tag{D-5}$$

For an uncorrected telescope ($c = 1$) and a 1-1/2 inch image tube ($D = 3.8$ cm) operating in the visible ($\lambda = 5000$ Å), Eq. (D-3) gives gives $\delta \geq 1.2 \times 10^{-3}$ cm corresponding with $\lesssim 80$ lp/mm. The value of ℓ from Eq. (D-4) is 1500 TV lines, maximum. Naturally, the inequality (D-3) holds for all shorter wavelengths and for a telescope with a coma corrector ($c \lessapprox 1$).

For practical reasons it does not seem likely that an image tube storage target can be made appreciably larger than 4 to 5 cm. In a high resolution tube ($\delta \approx .001$), Eq. (D-4) sets a limit on ℓ of 2000 to 2500 TV lines. The limit on ℓ for a low resolution tube ($\delta \approx .005$) is 400 to 500 lines. The f-ratio required to match the telescope resolution to that of an image tube is given by $f = \delta/\lambda$ and for $\delta = .005$, $\lambda = 5000$ Å an f/100 system is required, while an f/20 telescope is needed for a high resolution image tube. At short wavelengths the f-ratios become correspondingly larger, and focal lengths become impractically long if the primary mirror is used at full aperture. On the other hand, if the long focal ratios are obtained by stopping the telescope down, the exposure times to reach a given magnitude become comparatively long. Use of a smaller focal ratio than δ/λ reduces the resolution of the telescope correspondingly. If

$$f = \frac{\delta}{k\lambda} \tag{D-6}$$

then the resolution,

$$\alpha = \frac{k\lambda}{D} \tag{D-7}$$

and this is k times larger than the diffraction limit. Appendix A discusses the price one has to pay in performance for smaller than optimum focal ratios.